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$b \to s\gamma$ decays in the Left-Right Symmetric Model

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Abstract

We consider $b \to s\gamma$ decays in the Left-Right Symmetric Model. Values of observables sensitive to chiral structure such as the Λ polarization in the $\Lambda_b \to \Lambda\gamma$ decays and the mixing-induced CP asymmetries in the $B_{d,s} \to M^0\gamma$ decays can deviate in the LRSM significantly from the SM values. The combined analysis of P_Λ and A_{CP} as well as $\mathcal{BR}(b \to s\gamma)$ can be used to determine the model parameters.

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I. INTRODUCTION

The Left-Right Symmetric Model (LRSM) [1] based upon the electroweak gauge group $SU(2)_L \times SU(2)_R \times U(1)$ represents well-known extensions of the Standard Model (SM), and can lead to interesting new physics effects in the B system [2,3]. Due to the extended gauge structure there are both new neutral and charged gauge bosons, Z_R and W_R, as well as a right-handed gauge coupling, g_R. The symmetry $SU(2)_L \times SU(2)_R \times U(1)$ can be broken to $SU(2)_L \times U(1)$ by means of vacuum expectation values of doublet or triplet fields. As for $SU(2)_L \times U(1)$ symmetry breaking, we assume that it takes place when the scalar field Φ acquires the complex vacuum expectation value

$$< \Phi >= \begin{pmatrix} k_1 & 0 \\ 0 & k_2 \, e^{i\alpha} \end{pmatrix} . \tag{1}$$

After symmetry breaking the charged W_R mixes with W_L of the SM to form the mass eigenstates $W_{1,2}$ with eigenvalues $M_{1,2}$ and this mixing is described by two parameters; a real mixing angle ζ and a phase α,

$$\begin{pmatrix} W_1^+ \\ W_2^+ \end{pmatrix} = \begin{pmatrix} \cos\,\zeta & e^{-i\alpha} \sin\,\zeta \\ -\sin\,\zeta & e^{-i\alpha} \cos\,\zeta \end{pmatrix} \begin{pmatrix} W_L^+ \\ W_R^+ \end{pmatrix} . \tag{2}$$

The mixing angle ζ is small and can be expressed as

$$\zeta = \frac{2r}{1+r^2} \frac{M_1^2}{M_2^2}, \qquad (r \equiv k_2/k_1) \; . \tag{3}$$

In this model the charged current interactions of the right-handed quarks are governed by a right-handed CKM matrix, V_R , which , in principle, need not be related to its left-handed counterpart V_L. Here we examine the possibility of using the rare decays $b \to s\gamma$ as a new tool in exploring the parameter space of the LRSM. We assume manifest left-right symmetry, that is $|V_R| = |V_L|$ and $\kappa \equiv g_R/g_L = 1$.

The effective Hamiltonian of $b \to s\gamma$ decay in the LRSM, after ignoring m_s, is given by

$$H_{\rm eff}(b \to s\gamma) = -\frac{4 \; G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left[C_{7L} O_{7L} + C_{7R} O_{7R} \right], \tag{4}$$

where

$$O_{7L} = \frac{e}{16\pi^2} \; m_b \bar{s}_L \sigma^{\mu\nu} b_R \; F_{\mu\nu}, \qquad O_{7R} = \frac{e}{16\pi^2} \; m_b \bar{s}_R \sigma^{\mu\nu} b_L \; F_{\mu\nu}. \tag{5}$$

The magnetic moment operator coefficients are given by

$$
\begin{aligned}
C_{7L}(m_b) &= C_{7L}^{SM}(m_b) + \zeta \frac{m_t}{m_b} \frac{V_R^{tb}}{V_L^{tb}} e^{i\alpha} \left[\eta^{16/23} \tilde{F}(x_t) + \frac{8}{3}(\eta^{14/23} - \eta^{16/23}) \tilde{G}(x_t) \right] \\
&+ \frac{2r(1+r^2)}{(1-r^2)^2} \frac{m_t}{m_b} \frac{V_R^{tb}}{V_L^{tb}} e^{i\alpha} \left[\eta^{16/23} \tilde{F}_H(y_t) + \frac{8}{3}(\eta^{14/23} - \eta^{16/23}) \tilde{G}_H(y_t) \right], \qquad (6)
\end{aligned}
$$

$$
\begin{aligned}
C_{7R}(m_b) &= \zeta \frac{m_t}{m_b} \left(\frac{V_R^{ts}}{V_L^{ts}} \right)^* e^{-i\alpha} \left[\eta^{16/23} \tilde{F}(x_t) + \frac{8}{3}(\eta^{14/23} - \eta^{16/23}) \tilde{G}(x_t) \right] \\
&+ \frac{2r(1+r^2)}{(1-r^2)^2} \frac{m_t}{m_b} \left(\frac{V_R^{ts}}{V_L^{ts}} \right)^* e^{-i\alpha} \left[\eta^{16/23} \tilde{F}_H(y_t) + \frac{8}{3}(\eta^{14/23} - \eta^{16/23}) \tilde{G}_H(y_t) \right], \qquad (7)
\end{aligned}
$$

where

$$
C_{7L}^{SM}(m_b) = \eta^{16/23} F(x_t) + \frac{8}{3}(\eta^{14/23} - \eta^{16/23}) G(x_t) + \sum h_i \eta^{p_i} , \qquad (8)
$$

with $\eta = \alpha_s(M_1)/\alpha_s(m_b)$, $x_t = (m_t/M_1)^2$ and $y_t = (m_t/M_H)^2$, where M_H is the mass of the charged physical scalars. The various functions of x_t, y_t, and the coefficients h_i, and powers p_i can be founded in the Ref. [3].

II. OBSERVABLES SENSITIVE TO CHIRAL STRUCTURE

A. Branching fraction of inclusive decay $\mathcal{BR}(b \to s\gamma)$

The decay rate for inclusive $b \to s\gamma$ decay is given by

$$
\Gamma(b \to s\gamma) = \frac{G_F^2 m_b^5}{32\pi^4} \alpha_{em} |V_{ts}^* V_{tb}|^2 \left(|C_{7L}(m_b)|^2 + |C_{7R}(m_b)|^2 \right). \qquad (9)
$$

It is common practice to normalize this radiative partial width to the semileptonic rate

$$
\Gamma(b \to ce\bar{\nu}) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 f(\frac{m_c}{m_b}) \left[1 - \frac{2}{3\pi} \alpha_s(m_b) g(\frac{m_c}{m_b}) \right], \qquad (10)
$$

where $f(x) = 1 - 8x^2 - 24x^4 \ln x + 8x^6 - x^8$ represents a phase space factor, and the function $g(x)$ encodes next-to-leading order strong interaction effects [4]. In terms of the ratio R,

$$
R \equiv \frac{\Gamma(b \to s\gamma)}{\Gamma(b \to ce\bar{\nu})} = \frac{6}{\pi} \frac{|V_{ts}^* V_{tb}|^2}{|V_{cb}|^2} \frac{\alpha_{em}}{f(\frac{m_c}{m_b})} \frac{|C_{7L}(m_b)|^2 + |C_{7R}(m_b)|^2}{1 - \frac{2}{3\pi}\alpha_s(m_b) g(\frac{m_c}{m_b})}, \qquad (11)
$$

the $b \to s\gamma$ branching fraction is obtained by

$$
\mathcal{BR}(b \to s\gamma) = \mathcal{BR}(b \to ce\bar{\nu}) \times R \simeq \mathcal{BR}(B \to X_c l\nu)_{\text{exp.}} \times R \sim (0.105) \times R. \qquad (12)
$$

In Eqs. (8,9), we neglected the $1/m_b^2$ corrections. For $\mathcal{BR}(b \to s\gamma)$, we also use the present experimental value [5] of the branching fraction for $B \to X_s\gamma$ decay,

$$\mathcal{BR}(B \to X_s\gamma) = (3.15 \pm 0.35_{\rm stat} \pm 0.32_{\rm syst} \pm 0.26_{\rm model}) \times 10^{-4}. \tag{13}$$

B. Λ Polarization in $\Lambda_b \to \Lambda\gamma$ decay

One way to access the chiral structure is to consider the decay of baryons. From the experimental side the decay $\Lambda_b \to \Lambda\gamma$ is a good candidate, since the subsequent Λ decay $\Lambda \to p\pi$ is self analyzing [6]. The expected branching ratio is of order 10^{-5} and should be measurable at future hadronic B factories, HERA-B, BTeV and LHC-B. The chiral structure can be studied by measuring the polarization of Λ, via the angular distribution,

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}(1 + P_\Lambda \cos\theta), \tag{14}$$

where

$$P_\Lambda = \frac{|C_{7L}(m_b)|^2 - |C_{7R}(m_b)|^2}{|C_{7L}(m_b)|^2 + |C_{7R}(m_b)|^2}, \tag{15}$$

and θ is the angle between the direction of the momentum of Λ in the rest frame of Λ_b and the direction of the Λ polarization in the Λ rest frame.

C. Mixing-induced CP Asymmetry in $B_{d,s} \to M^0\gamma$ decays

Next, we consider the mixing-induced CP asymmetry for $B_{d,s} \to M^0\gamma$ decays [7]. Here M^0 is any hadronic self-conjugate state, with CP eigenvalue $\xi = \pm 1$. The decay amplitudes are denoted by

$$\begin{aligned}
A(\bar{B}_{d,s} \to M^0\gamma_{_L}) &= A\ \cos\ \psi\ e^{i\phi_L}, \\
A(\bar{B}_{d,s} \to M^0\gamma_{_R}) &= A\ \sin\ \psi\ e^{i\phi_R}, \\
A(B_{d,s} \to M^0\gamma_{_R}) &= \xi\ A\ \cos\ \psi\ e^{-i\phi_L}, \\
A(B_{d,s} \to M^0\gamma_{_L}) &= \xi\ A\ \sin\ \psi\ e^{-i\phi_R}.
\end{aligned} \tag{16}$$

Here the parameter ψ gives the relative amount of left-polarized photons compared to right-polarized photons in $\bar{B}_{d,s}$ decays, and $\phi_{L,R}$ are CP-odd weak phases. Using the time dependent rates $\Gamma(t)$ and $\bar{\Gamma}(t)$ for $B_{d,s} \to M^0\gamma$ and $\bar{B}_{d,s} \to M^0\gamma$ respectively, one finds a time-dependent CP asymmetry

$$A(t) = \frac{\Gamma(t) - \bar{\Gamma}(t)}{\Gamma(t) + \bar{\Gamma}(t)} = \xi \; A_{CP} \; \sin(\Delta m t), \tag{17}$$

where

$$A_{CP} \equiv \sin(2\psi) \sin(\phi_{_M} - \phi_{_L} - \phi_{_R}), \tag{18}$$

and Δm and $\phi_{_M}$ are the mass difference and phase in the $B_{d,s} - \bar{B}_{d,s}$ mixing amplitude.

In terms of $C_{7L(R)}$, the ψ and $\phi_{L(R)}$ are given by

$$\sin(2\psi) = \frac{2|C_{7L}(m_b) \; C_{7R}(m_b)|}{|C_{7L}(m_b)|^2 + |C_{7R}(m_b)|^2} \; , \tag{19}$$

$$\phi_{_L} = \sin^{-1}\left(\frac{Im(C_{7L}(m_b))}{|C_{7L}(m_b)|}\right), \qquad \phi_{_R} = \sin^{-1}\left(\frac{Im(C_{7R}(m_b))}{|C_{7R}(m_b)|}\right). \tag{20}$$

The phase of $B_{d,s} - \bar{B}_{d,s}$ mixing can be also affected by new LRSM contributions [8], and is given by $\phi_{_M} = \phi_{_M}^{SM} + \delta_{_M}$ where

$$\delta_{_M} = \tan^{-1}\left(\frac{h \; \sin\sigma}{1 + h \; \cos\sigma}\right). \tag{21}$$

Here $h = |M_{12}^{LR}|/|M_{12}^{SM}|$ measures the relative size of the left-right contribution to the non-diagonal element M_{12} and can be written as

$$h = F(M_2)\left(\frac{1.6 \text{ TeV}}{M_2}\right)^2 + \left(\frac{12 \text{ TeV}}{M_H}\right)^2, \tag{22}$$

where $F(M_2)$ is a complicated function of the M_2. The phase σ can be expressed as

$$e^{i\sigma} = -\frac{V_R^{td*} \; V_R^{tb}}{V_L^{td*} \; V_L^{tb}} \; , \qquad e^{i\sigma} = -\frac{V_R^{ts*} \; V_R^{tb}}{V_L^{ts*} \; V_L^{tb}} \; , \tag{23}$$

for B_d and B_s systems, respectively. And $\phi_{_M}^{SM} = 2\beta$ and $\phi_{_M}^{SM} = 0$ for B_d and B_s systems, respectively (where $-\beta$ is the phase of V_{td} in the standard convention).

III. COMBINED ANALYSIS

In this Section, we perform the combined analysis of three observables, $\mathcal{BR}(b \to s\gamma)$, P_Λ and A_{CP}. Fig. 1 is the contour plot for $\mathcal{BR}(b \to s\gamma)$ and P_Λ on the $(|C_{7L}(m_b)|\ ,\ |C_{7R}(m_b)|)$ plane. Two solid curves indicate the 1σ range of the measured values of inclusive $\mathcal{BR}(b \to s\gamma)$. Three dashed lines correspond to three different values of P_Λ, as indicated in the figure. From the measurements of $\mathcal{BR}(b \to s\gamma)$ and P_Λ, one can determine the magnitudes $|C_{7L}(m_b)|$ and $|C_{7R}(m_b)|$ separately. And the measurement of A_{CP} would give some informations on the phases of $C_{7L}(m_b)$ and $C_{7R}(m_b)$.

A. Simple Case

First, we consider a simple case. We assume $V_L = V_R$ and ignore the contributions from $W_2^\pm$ and charged physical scalars. Then only two new physics parameters, ζ and α, remain. To illustrate the usefulness of P_Λ measurements, let's consider $\alpha = 0$ case. Fig. 2(a) shows the dependence of inclusive $\mathcal{BR}(b \to s\gamma)$ on the mixing angle ζ in this case. Two horizontal dashed lines indicate the 1σ range of the present measured values of inclusive $\mathcal{BR}(b \to s\gamma)$. It is clear from the figure that the SM result is essentially obtained when $\zeta = 0$, and also that a conspiratorial solution occurs when $\zeta \sim -0.01$. These two cases are indistinguishable, and even independent of any further improvements in the measurement of the inclusive $\mathcal{BR}(b \to s\gamma)$. However, if P_Λ in $\Lambda_b \to \Lambda\gamma$ decays is measured in addition, these two solutions are definitely distinguishable as indicated in Fig. 2(b), which shows the dependence of P_Λ on the mixing angle ζ. The $\zeta \sim 0$ case corresponds to $P_\Lambda \sim +1$, and the $\zeta \sim -0.01$ case corresponds to $P_\Lambda \sim -1$.

When we vary the phase α between 0 and π radian, P_Λ can have all the possible values from $+1$ to -1, while satisfying the inclusive $\mathcal{BR}(b \to s\gamma)$ constraints. Figs. 3(a) and 3(b) show the dependence of P_Λ on ζ and α respectively, where we impose the present experimental $\mathcal{BR}(B \to X_s\gamma)$ constraints. The larger magnitudes of ζ gives larger deviations of P_Λ from the SM expectation, $P_\Lambda(SM) = +1$. Because the measurements of $\mathcal{BR}(b \to s\gamma)$ and P_Λ determine only the magnitudes of $C_{7L}(m_b)$ and $C_{7R}(m_b)$, the ζ can be determined up to the sign ambiguity.

Next, we consider A_{CP} in the radiative $B_{d,s}$ decays, $B_{d,s} \to M^0 + \gamma$, *eg.*, $B_d \to K^* + \gamma$

and $B_s \to \phi + \gamma$. The dependences of A_{CP} on the ζ and α is shown in Figs. 4(a) and 4(b), respectively, for $B_d \to M^0\gamma$ decay. And in Figs. 4(c) and 4(d) we show the dependence of A_{CP} on the ζ and α for $B_s \to M^0\gamma$ decay. Here we impose the present experimental inclusive $\mathcal{BR}(B \to X_s\gamma)$ constraints [5]. For numerical value of β, we use the central value of the recent CDF measurement [9] of sin 2β from $B_d \to J/\psi + K_s$,

$$\sin\ 2\beta = 0.79^{+0.41}_{-0.44}. \tag{24}$$

It is clear from the figures that A_{CP} can have rather large values between -20% and 90% for $B_d \to M^0\gamma$ decay, and up to $\pm 60\%$ for $B_s \to M^0\gamma$ decay, while the SM expectation values $A_{CP}(SM)$ are almost zero. We can see that different sign of ζ with same magnitude correspond to different values of A_{CP}. Therefore, the sign ambiguity of ζ determined from P_Λ measurements can be resolved by measuring A_{CP}. Moreover, P_Λ and A_{CP} have definite correlations, as shown in Figs. 5(a) and (b) for $B_d \to M^0\gamma$ and for $B_s \to M^0\gamma$, respectively. Any deviations from these correlations would indicate the failure of the manifest left-right symmetric scenario which we assume in this subsection.

B. General Case

Now we consider more general case. We assume that the elements of V_R have arbitrary phase. We also consider the contributions from $W_2^\pm$ and charged physical scalars. In this case, $C_{7L}(m_b)$ depends on the parameters; r, ω_1, M_2 and M_H. And $C_{7R}(m_b)$ depends on r, ω_2, M_2 and M_H. The parameters ω_1 and ω_2 are defined as

$$e^{i\omega_1} \equiv \frac{V_R^{tb}}{V_L^{tb}} e^{i\alpha}, \qquad e^{i\omega_2} \equiv \frac{V_R^{ts}}{V_L^{ts}} e^{i\alpha}. \tag{25}$$

For further numerical calculations, we fix $M_2 = 1.6$ TeV and $M_H = 12$ TeV.

While the magnitude of $C_{7L}(m_b)$ depends on the r and ω_1, the magnitude of $C_{7R}(m_b)$ only on the r but not on the ω_2. Therefore, P_Λ depends on the r and ω_1 but not on the ω_2. The dependences of P_Λ on the r and ω_1 are shown in Figs. 6(a) and 6(b), respectively. For large r, the value of P_Λ can be largely deviated from the SM value due to the large contributions from charged physical scalars even though ζ is small. From the measurement of P_Λ we can determine the values of r and ω_1 (up to discrete ambiguity) for given values of M_2 and M_H.

In $B_d \to M^0\gamma$ decays, A_{CP} has additional dependences on another new phase ω_3 and also on phase β through ϕ_M, the phase of $B_d - \bar{B}_d$ mixing. The phase ω_3 is defined by

$$e^{i\omega_3} \equiv \frac{V_R^{td}}{V_L^{td}} e^{i\alpha} \ . \tag{26}$$

The dependence of A_{CP} on ω_2 appear only through ϕ_R in this case. And the phase of $B_d - \bar{B}_d$ mixing, ϕ_M would be determined independently from the measurement of $A_{J/\Psi K_s}$, *i.e.* the mixing induced CP aymmetry in the $B_d \to J/\Psi + K_s$ decays [9],

$$A_{J/\Psi K_s} = \sin(\phi_M) \ . \tag{27}$$

Therefore, in addition to P_Λ, for the B_d system the value of ω_2 can be determined up to discrete ambiguity for given values of M_2 and M_H from the measurement of A_{CP}. In $B_s \to M^0\gamma$ decays, A_{CP} has dependence on the ω_2 through ϕ_R and also on ϕ_M. As can be seen from Eq. (18), A_{CP} can have any values between $-\sin(2\Psi)$ and $+\sin(2\Psi)$ depending on the ω_2. The dependences of $\sin(2\Psi)$, the maximum value of A_{CP}, on the r and ω_1 are shown in the Figs. 7(a) and 7(b), respectively, for $B_{d,s} \to M^0\gamma$ decays. It is clear that the values of A_{CP} can be largely deviated from the SM prediction. From the measurement of A_{CP} in addition to P_Λ, the value of ω_2 can be also determined up to discrete ambiguity for given values of M_2 and M_H.

To summarize, in this paper we considered the radiative B hadron decay in the Left-Right Symmetric Model (LRSM). Values of observables sensitive to chiral structure such as the Λ polarization in the $\Lambda_b \to \Lambda\gamma$ decays and the mixing-induced CP asymmetries in the $B_{d,s} \to M^0\gamma$ decays can deviate in the LRSM significantly from the SM values. The combined analysis of P_Λ and A_{CP} as well as $\mathcal{BR}(b \to s\gamma)$ can be used to determine the model parameters. From the correlations between P_Λ and A_{CP}, the validity of the manifest left-right symmetry scenario can also be tested.

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FIGURES

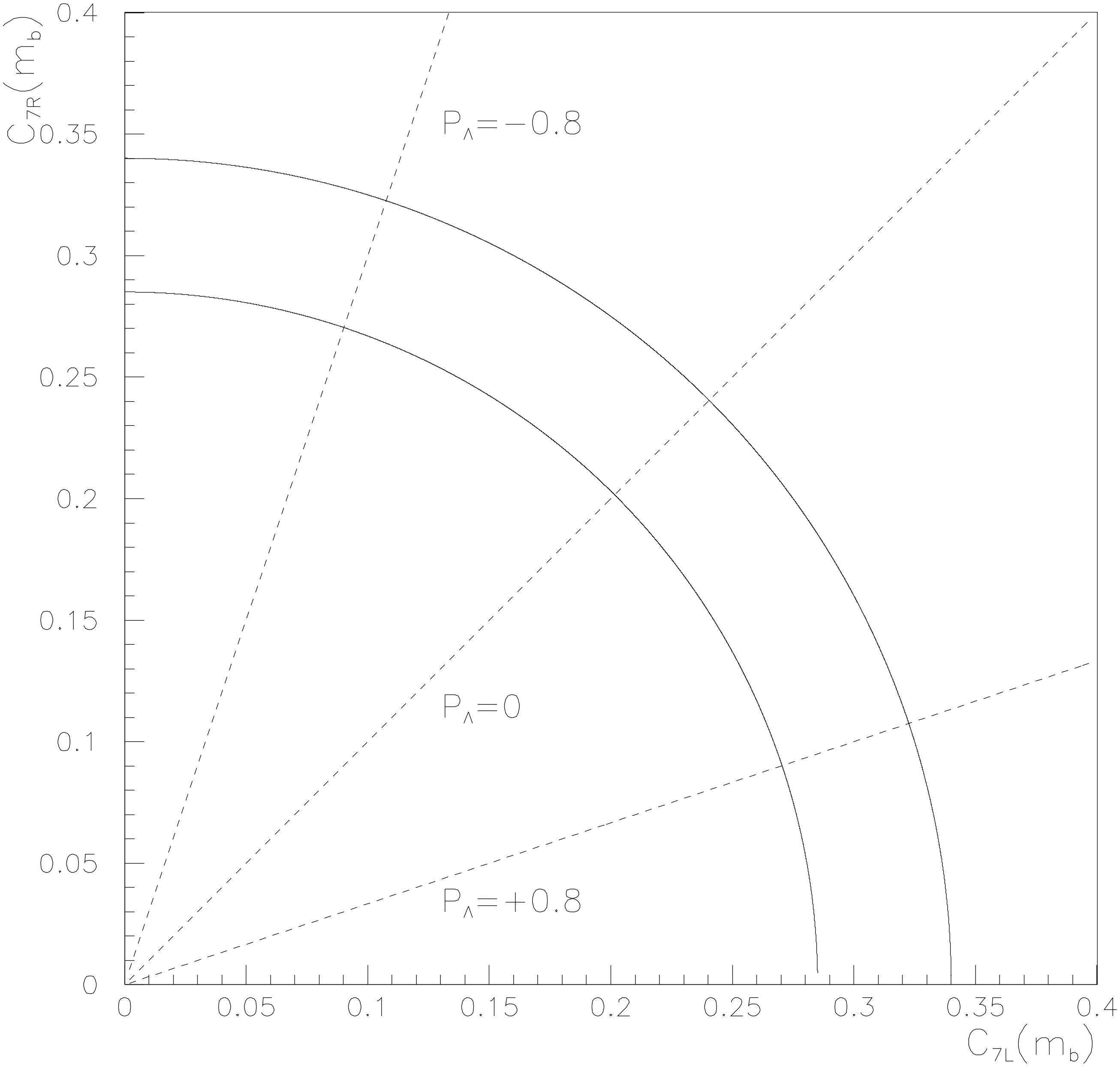


FIG. 1. Contour plots for the inclusive $\mathcal{BR}(b \to s\gamma)$ and P_Λ. Two solid curves indicate the 1σ range of the present measured values of inclusive $\mathcal{BR}(B \to X_s\gamma)$.

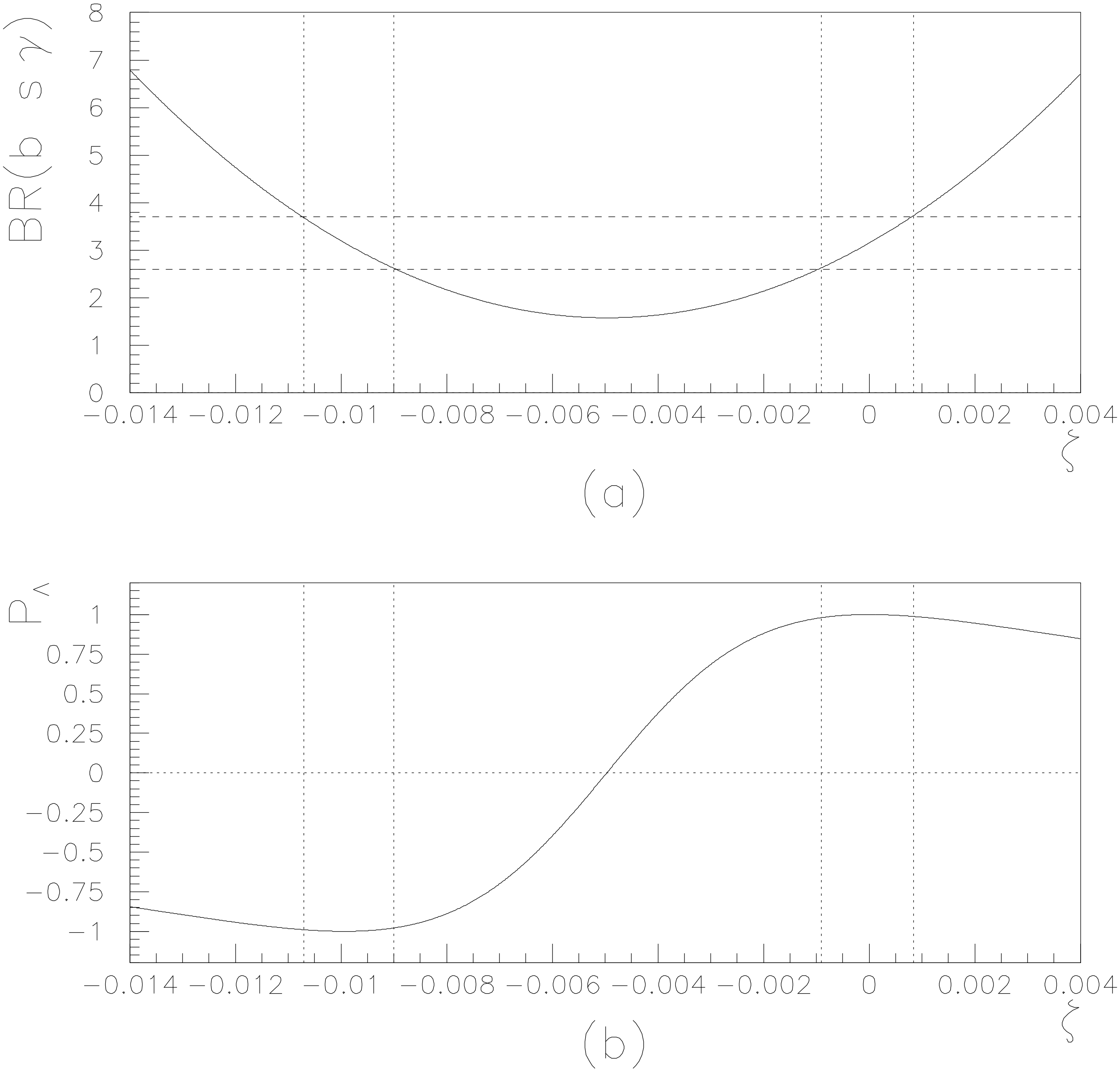
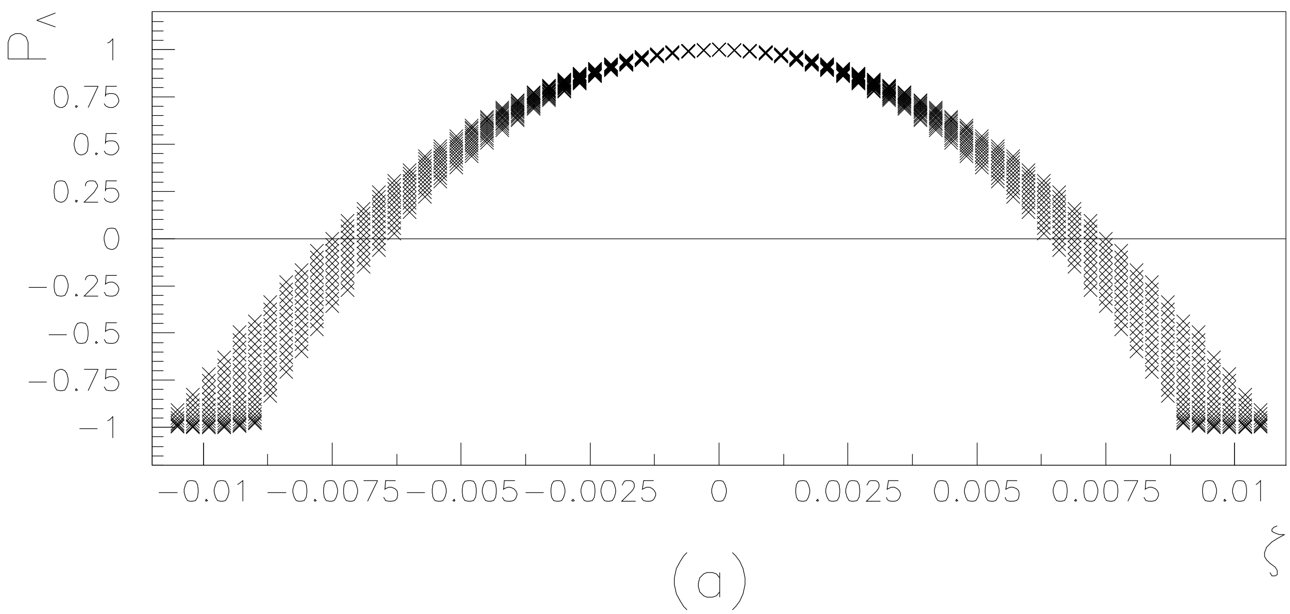


FIG. 2. (a) Dependence of inclusive $\mathcal{BR}(b \to s\gamma)$ on mixing angle ζ. Two horizontal dashed lines indicate the 1σ range of the present measured values of inclusive $\mathcal{BR}(B \to X_s\gamma)$. (b) Dependence of P_Λ on mixing angle ζ. In both cases we fix $\alpha = 0$.



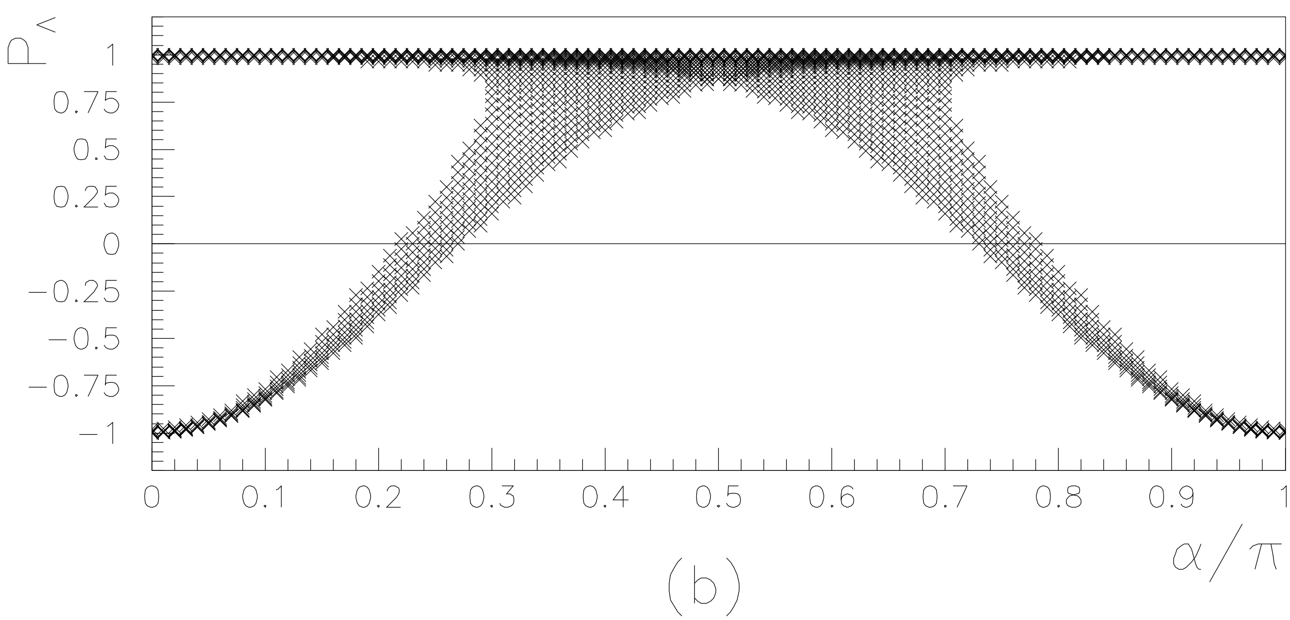


FIG. 3. Dependence of P_Λ on (a) ζ, and on (b) α. Here we imposed the present inclusive $\mathcal{BR}(B \to X_s\gamma)$ constraints.

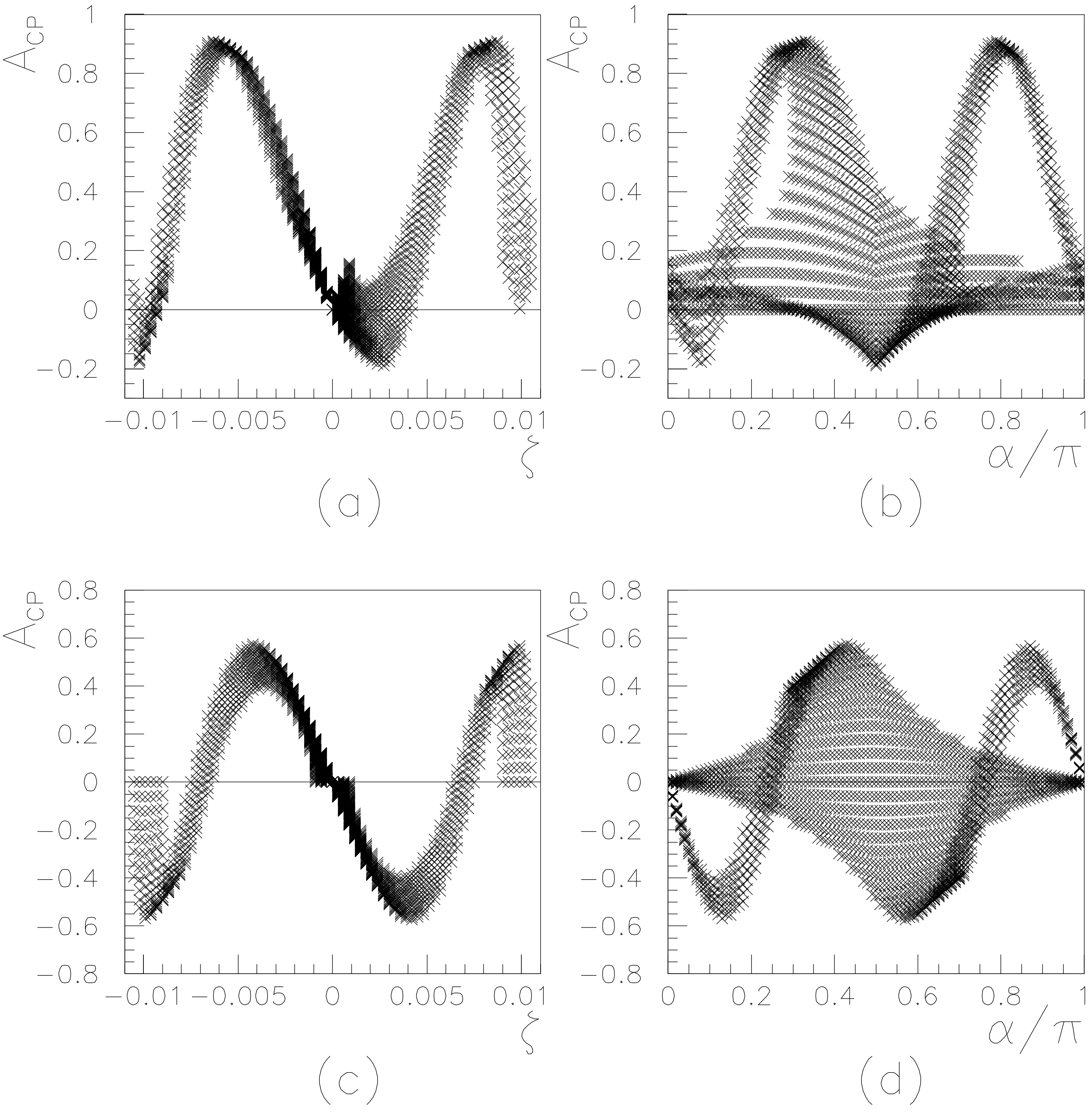


FIG. 4. Dependence of A_{CP} on ζ, and on α is shown in (a) and (b), respectively, for $B_d \to M^0\gamma$ decay; and in (c) and (d) ,respectively, for $B_s \to M^0\gamma$ decay. Here we imposed the present inclusive $\mathcal{BR}(B \to X_s\gamma)$ constraints.

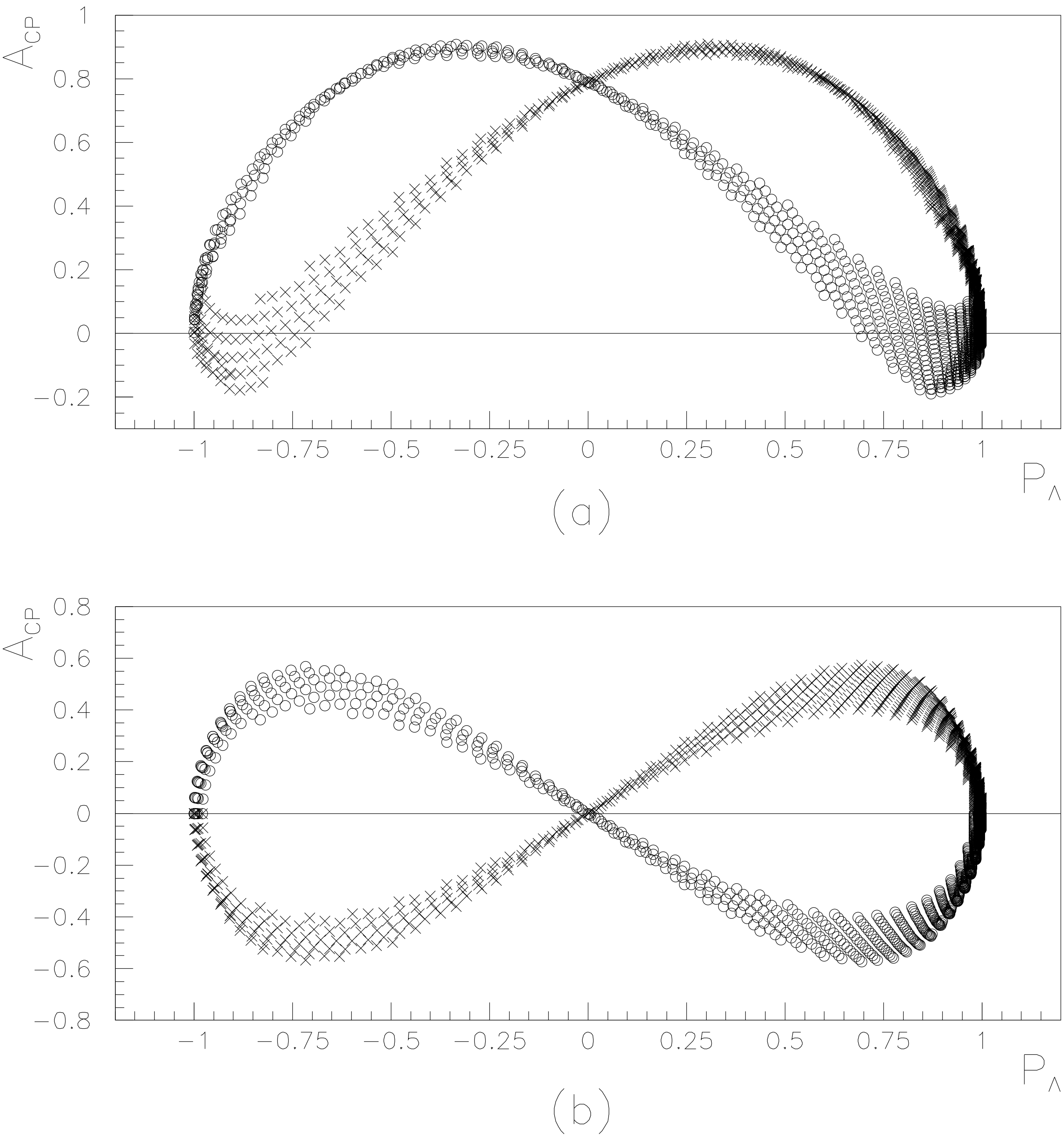


FIG. 5. Correlations between A_{CP} and P_Λ: (a) and (b) correspond to $B_d \to M^0\gamma$ and $B_s \to M^0\gamma$ decays, respectively. Here we imposed the present inclusive $\mathcal{BR}(B \to X_s\gamma)$ constraints.

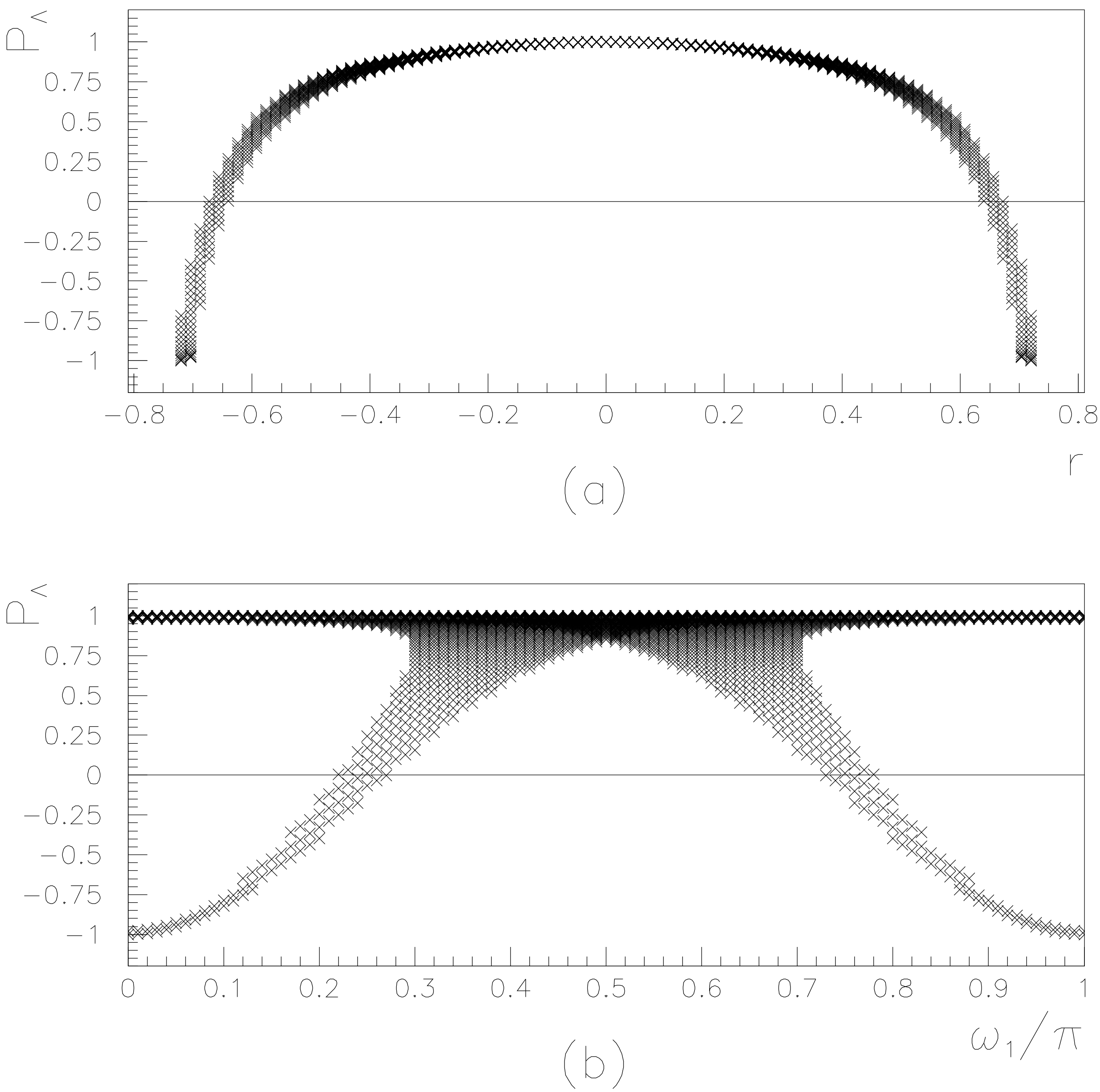


FIG. 6. Dependences of P_Λ on (a) r, and on (b) ω_1. Here we imposed the present inclusive $\mathcal{BR}(B \to X_s\gamma)$ constraints and fix $M_2 = 1.6$ TeV and $M_H = 12$ TeV.

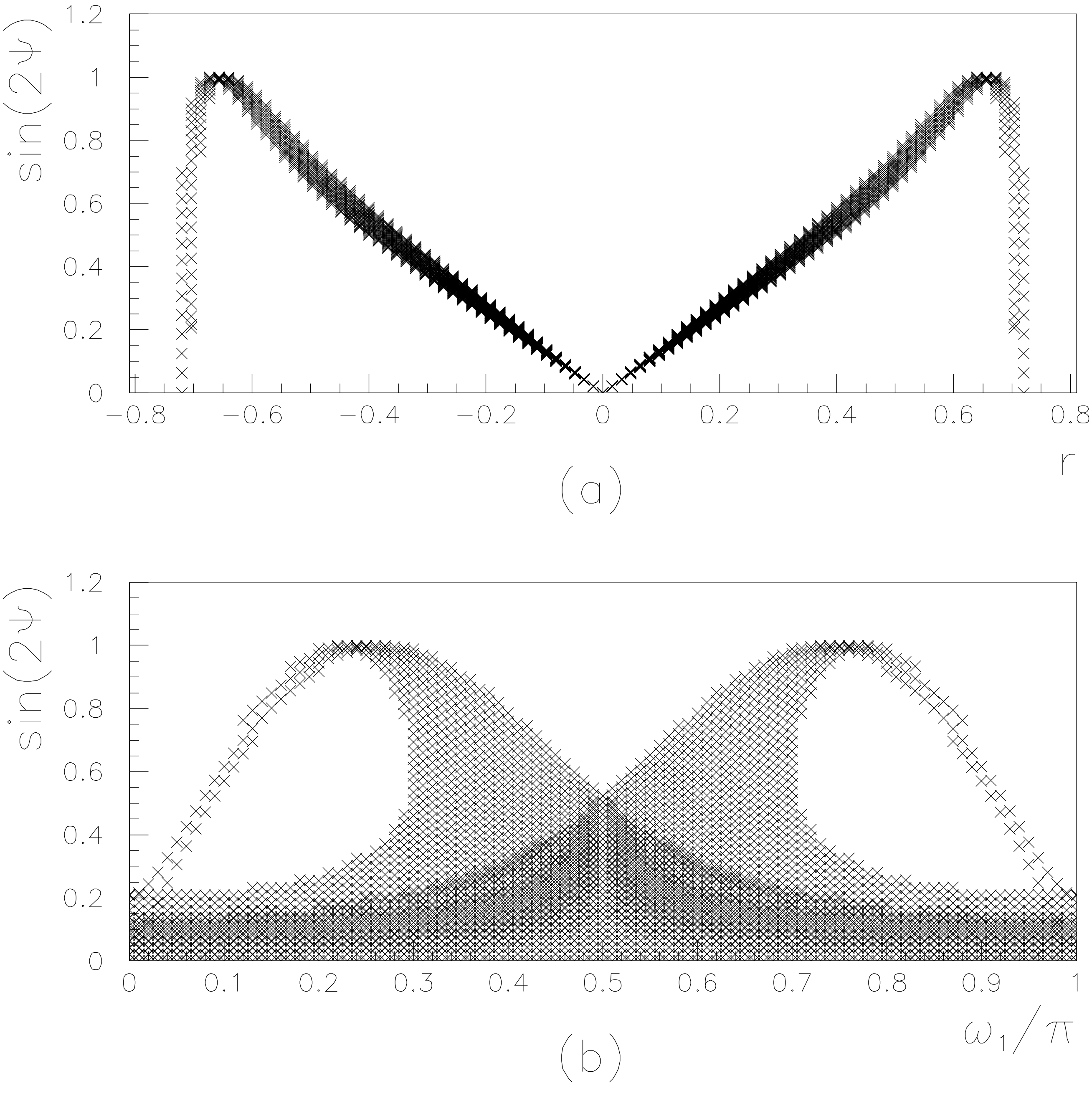


FIG. 7. Dependences of $\sin(2\Psi)$, the maximum value of A_{CP}, on r, and on ω_1 are shown in (a) and (b), respectively, for $B_{d,s} \to M^0\gamma$ decay. Here we imposed the present inclusive $\mathcal{BR}(B \to X_s\gamma)$ constraints and fix $M_2 = 1.6$ TeV and $M_H = 12$ TeV.